ISSUES IN OBSTACLE DETECTION FOR AUTONOMOUS MINING AND CONSTRUCTION VEHICLES [1]

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Abstract: This paper discusses a number of key issues for the development of robust obstacle detection systems for autonomous mining and construction vehicles. A taxonomy of obstacle detection systems is described. An overview of the state-of-the-art in obstacle detection for outdoor autonomous vehicles is presented with their applicability to the mining and construction environments noted. The issue of so-called *fail-safe* obstacle detection is then discussed. Finally, we describe the development of an obstacle detection system for a mining vehicle.

Keywords: obstacle detection, terrain mapping, mining, construction, fail-safe

1. INTRODUCTION

Reliable obstacle detection is an essential element of an autonomous mining or construction vehicle system. An autonomous vehicle must be capable of detecting potentially dangerous obstacles that would endanger the vehicle itself, other vehicles, personnel or expensive site infrastructure while navigating through the mine or construction site. Autonomous vehicles will not be deployed in the field until robust obstacle detection systems have been developed.

The development of robust obstacle detection systems for these vehicles is difficult because of the relatively harsh conditions encountered in the mining and construction environments. The operating environment could include rain, dust, mud, high humidity, diesel fumes (small particles), extremes of temperature, severe vibration, extreme vehicle pitching and rolling, and bright light sources (e.g. the sun).

The aims of this paper are as follows:

(1) To present a brief overview of the state-of-the-art in obstacle detection for outdoor autonomous vehicles and to comment on their applicability to the mining and construction environments.
(2) To define what is meant by the term *fail-safe* with regard to obstacle detection.
(3) To convince the reader that directly detecting obstacles cannot be made fail-safe and hence local terrain mapping is the best way in which to approach the problem.

1.1 *What is an obstacle?*

It is important to define what an obstacle is before we discuss how an obstacle may be detected. We define an obstacle as something that will cause dangerous or undesirable behaviour if hit

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by the autonomous vehicle. Three general classes of obstacles are:

(1) people,
(2) other vehicles and
(3) other roadway obstacles (excluding people and other vehicles).

The third class of obstacles can include anything from a rock lying in the middle of a mine haul road to a mobile lighting tower used on a construction site.

1.2 *Structure of the paper*

In the following section we describe a taxonomy of obstacle detection systems. Section 3 then gives an overview of the state-of-the-art in obstacle detection for outdoor autonomous vehicles. Section 4 raises the issue of so-called *fail-safety*. Section 5 briefly describes an obstacle detection system being developed by our group for a large mining vehicle. Finally, Section 6 lists some conclusions.

2. A TAXONOMY OF OBSTACLE DETECTION

There are two distinct approaches to the obstacle detection problem. The first attempts to detect the obstacles themselves by either actively illuminating a scene and waiting for reflections, or by passively receiving energy from potential obstacles. The second does not look for obstacles directly, instead the free-space, or navigable area, in-front of the vehicle is sought. Here, anything that is not navigable is considered an obstacle. This is a local terrain mapping problem. It is clear from the literature that both of these approaches are referred to as obstacle detection or obstacle avoidance, even though only the first approach directly detects obstacles.

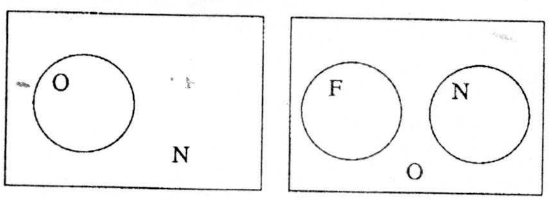

Fig. 1. Left: direct obstacle detection. Right: the terrain-mapping approach.

An important distinction between these two approaches is how *null* information is used [2]. The lack of a return signal from an active system, or the lack of any radiated energy in a passive system is referred to as null information, or a null return.

[2] This is important when considering the robustness of a system (Section 4)

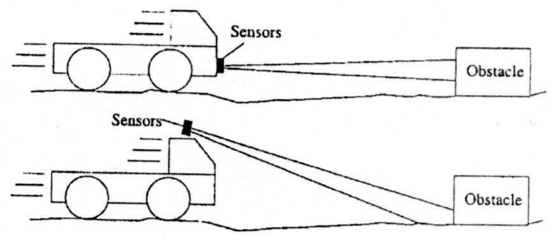

Fig. 2. Top: direct obstacle only detection. Bottom: the terrain-mapping approach.

Figure 1 shows some Venn diagrams of the situation to highlight the key difference between the two approaches. In the first approach the set of non-null returns is classified as the set of obstacles, O.

$$O = N' \quad (1)$$

where N is the set of null returns.

However, the second approach detects the set of free-space, F, and also has a set of null returns N. Here then, the set of obstacles, O, is given by:

$$O = (F \cup N)' \quad (2)$$

The two approaches normally require different sensor placements. The first approach normally requires sensors to be mounted on the front of the vehicle, typically low down so as not to miss any short obstacles. The sensors are normally aligned with the direction of travel of the vehicle (Fig. 2). The second approach (terrain mapping) requires an elevated sensor position to view the local terrain. Most laser-based systems also require additional sensors giving positional data to aid with the integration of successive scans in order to build the map.

3. THE STATE-OF-THE-ART

Obstacle detection may also be categorised by the sensor(s) used. The four most commonly used sensors being:

- radio tags,
- radar,
- lasers and
- cameras (computer vision).

The remainder of this section will discuss the merits and problems of these four categories of system.

3.1 *Radio tags*

Probably the cheapest and simplest form of obstacle detection systems are those based on radio tags. All site personnel and vehicles carry a tag.

The tags can be active or passive. In the case of passive tags, the autonomous vehicle carries both a radio transmitter and receiver. The vehicle transmits a signal to all tags in range and the tags in range reply. The signal may be transmitted all around the vehicle, or just in the direction of travel of the autonomous vehicle. In the case of active tags, the vehicle only has a receiver and each tag transmits its own signal.

There are three fundamental problems with tag systems:

(1) The transmitted signal power chosen is determined from signal frequency and the required maximum range at which you wish to detect obstacles. The signal power must be calculated assuming some nominal and static environmental factors (such as air temperature, humidity, amount of free space all around the vehicle etc). However, the actual range of the radio signal will vary depending on the time varying terrain and weather conditions. It is therefore impossible to guarantee that all tags within the maximum range receive the signal.
(2) Not all obstacles will have a tag. It is simply not feasible to tag every potential obstacle in a mine or on a construction site. Potential obstacles include construction materials and fallen rocks from mine haul trucks.
(3) It is impossible for the autonomous vehicle to detect a non-functioning or faulty tag. A dead tag is equivalent to no tag.

Radio tag based systems are therefore only suitable for personnel and other vehicle detection and should certainly not be relied on as the sole means of detection by an autonomous vehicle. Commercially available tag systems have been designed as a human driver warning system only, where the driver acts as the other means of obstacle detection, and it is still their responsibility if there is an accident.

3.2 *Radar based systems*

Radar based collision warning systems and headway control systems based on radar have been developed by a number of research groups and companies around the world as part of the various Intelligent Vehicle Highway Systems (IVHSs) during the late 1980's and throughout the 1990's. Examples of such systems are to be found in [1–9]. Systems designed for large highway trucks are now in everyday use in the USA. These systems use a forward looking radar to warn a truck driver if they are approaching a vehicle ahead too quickly. Some systems are also capable of full headway control providing intelligent cruise control function. The collision warning sensor is used as an input to the trucks cruise control system enabling the truck to maintain a safe distance to the vehicle in-front.

As a rule of thumb, radar will detect a target if the target size is bigger than the wavelength of the radar carrier frequency. Increasing the radar's operating frequency increases its angular resolution and reduces the physical size of the radar's antenna. As a result of the advantages of high frequency operation, millimetre radar is being developed for automotive applications. Much of the current work on automotive radar development is in the 77 GHz band.

While the automotive systems described above rely on the obstacle itself to reflect the radar signal, it is possible to use targets placed on the obstacles[10] (much like the tags described in the previous section). The targets are carefully designed to reflect radar energy back to the receiver. In this way it is possible to navigate a vehicle[10], but also to perform detection of other vehicles.

A critical assumption of most of the automotive radar based obstacle detection systems is that the world is roughly flat, and therefore it is assumed that the vehicle will not pitch or roll significantly. This is a reasonable assumption for a car travelling at speed on a highway. The implication of this approximation is that the problem is a 2-dimensional one, i.e. vehicles can only move on the road plane. The major difference between this situation and the real situation encountered in the mining and construction environments is that mine and construction vehicles can pitch and roll significantly due to uneven road surfaces (assuming that they are even driving on a road!). It is therefore highly unlikely that any of the current automotive based systems would be applicable to the mining or construction environments. One exception to this might be on haul trucks in open pit coal mines, where the roads are often of high quality, and other vehicles would be detected.

3.3 *Laser based systems*

An alternative to radar for obstacle detection is the use of lasers. Lasers have been used frequently by researchers for obstacle detection for highway driving. Examples may be found in [11–13]. These systems attempt to directly detect potential obstacles by scanning the laser beam in-front of the vehicle. As with many of the radar systems, the flat-world assumption is made, and hence significant vehicle pitch or roll will degrade the system's performance.

Free-space finding laser-based systems have also been developed. The most famous use of such an obstacle detection system was that of the

Sojourner Mars rover[14]. This system mapped the local terrain ahead of the rover using a laser and diffraction grating and a CCD camera. The diffraction grating produced 15 points/spots 50 cm ahead of the rover. This system had no moving parts and was hence very robust. Because it relied on the forward motion of the rover to move the line of spots across the scene, odometry was required to integrate the data.

The European Panorama project[15] also developed a successful free-space finding laser-based system. Here, a scanning laser rangefinder was used to scan ahead of the vehicle. Like the Sojourner system, the motion of the vehicle moved the scanned laser beam across the scene. Accurate odometry, inertial data and GPS was available to accurately integrate the data. A similar configuration was used with the highly successful Navlab 4 off-road vehicle[16].

Laser based systems do have some significant limitation including:

- lack of penetration through fog or dust (this is wavelength dependent);
- eye safety — this may be an issue when humans are near by;
- moving parts — the mechanical scanning systems must be robust enough to survive the extreme vibrations encountered in the mining and construction environments.

3.4 *Vision based systems*

The use of computer vision systems for obstacle detection by researchers has been widespread. The popularity of computer vision is probably due to the fact that the human researchers themselves possess a vision system, and because the sensors and computing hardware are relatively inexpensive. Systems can be categorised in a number of ways. Firstly, by the number of cameras used, or secondly by the image analysis technique used.

Automotive based obstacle detection systems have been developed as part of the IVHS programmes around the world. Some of these systems use a single camera and attempt to *recognise* the obstacles (cars, trucks, etc) directly from the grey-level image[17–19]. Other systems use two (stereo) or more cameras to produce a range image. The range image may then be interpreted to find obstacles directly, or to map the free-space[20]. The Navlab 2 off-road vehicle successfully used a stereo camera system for obstacle detection[16].

Computer vision techniques suffer from the same poor visibility in fog and dust as do laser range finders. Visual techniques also require *good* lighting and often require excessive amounts of computing power (although this will become less of a problem with the constant improvement of computing power).

3.5 *Summary*

In summary, it is clear from the literature that the most successful obstacle detection systems for the unstructured and time-varying environments found in mines and construction sites have been based on local terrain mapping. The automotive type systems that are based on detecting obstacles directly have been designed with a smooth road in mind, and they are therefore not applicable to the mines and construction environment. It is also clear that systems based on lasers have so far been the most successful, even though lasers have well-known limitations in poor weather and dusty conditions. The literature is also quite clear that both radar and computer vision based systems will only get better, and may outperform laser systems in the relatively near-future.

4. FAIL-SAFETY

When developing an obstacle detection system, the ultimate goal is to create a so-called "fail-safe" system. Potential users of autonomous vehicles do, and will quite probably continue to demand that any obstacle detection system used by the vehicle is fail-safe. But what is meant by fail-safe?

4.1 *Definition*

The authors found two relevant definitions of *fail-safe*[21]:

(1) incorporating some feature for automatically counteracting the effect of an anticipated possible source of failure
(2) having no chance of failure: infallibly problem free

These two definitions at first glance look very similar. However, on further examination, it is easy to see that the definitions are radically different. Definition 1 is perhaps the definition most engineers have in mind when creating a fail-safe system. The key word in this definition is the word *anticipated*. This definition implies that a fail-safe system will in-fact fail if an unanticipated source of failure occurs.

Unfortunately, it is likely that the users of a fail-safe obstacle detection system have definition 2 in mind. That is, the fail-safe system can never fail, or certainly not fail in a way which will cause damage or injuries.

It is therefore critical that researchers and users understand and agree on what they mean by fail-safety.

4.2 *Direct obstacle detection*

In the case of a direct obstacle detection system (Section 2) for autonomous navigation the decision to move forward is based on null information, i.e. no obstacles were found in the path of the vehicle. But, there are two sources of null information. The first is that there are indeed no obstacles. However, the second is that the system has failed to detect an obstacle for whatever reason [3]. Hence, trying to directly detect obstacles alone in a time-varying and unstructured environment (such as a mine or construction site) can never be made fail-safe.

This very simple and obvious fact implies that many of the types of obstacle detection systems and techniques described in Section 3 can never be made fail-safe, and will hence never be applicable in isolation to truly autonomous vehicles. They are only useful in warning roles, where other systems (including humans) are available to correct potential failures.

4.3 *Finding free-space*

While it is impossible to create a fail-safe obstacle detection system based on no detection of obstacles (null information), it *maybe* possible to create a fail-safe system based on the existence on free-space, or navigable area, in-front of the vehicle (positive information). Here the system must detect/map the terrain it is going to move through and decide if there is enough free-space to drive through/over. Any sensor failures, or failure to detect the local terrain in such a system will produce null information, which in this case is invalid. Hence, the system will know when failure has occurred.

It should be noted that one reason the automotive systems developed so far do not map the navigable terrain in-front of the vehicle is because it has not been technically possible to do so at the high speeds that these vehicles travel at. This may change in the future with the reduction in price of radars and the increased performance of DSPs.

5. OBSTACLE DETECTION FOR AN LHD

In 1996 our group, in conjunction with the University of Sydney, mounted an array of sensors to a Load-Haul-Dump (LHD) truck (Fig. 3) used in underground metal mines[22]. Data were collected for the purpose of developing algorithms for both navigation and obstacle detection of the vehicle. The results of this exercise were very promising and a full-scale industry sponsored project to fully automate the driving and dumping functions of an LHD commenced in July 1998. A critical element of this project is to develop a robust obstacle detection system.

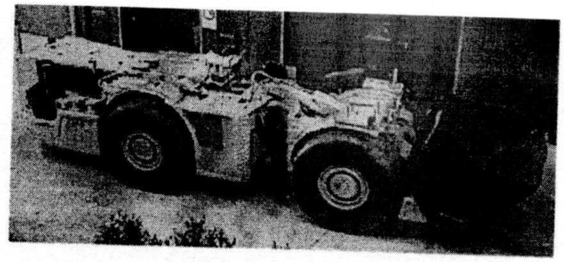

Fig. 3. A Load-Haul-Dump (LHD) truck.

The obstacle detection system will use two Erwin-Sick Proximity Laser Scanners (PLSs) — one looking forwards, and one backwards as an LHD travels equally well in either direction. Our aim is to map the terrain up to 10m in-front of the vehicle. The system must be capable of detecting non-traversable obstacles and bringing the LHD to a complete stop from 30km/h. These laser scanners gave very good results during our field-trial (Fig. 4). A full six-degree-of-freedom inertial platform, Doppler radar and odometry is currently being constructed which will be used to integrate the laser data and build the local terrain map.

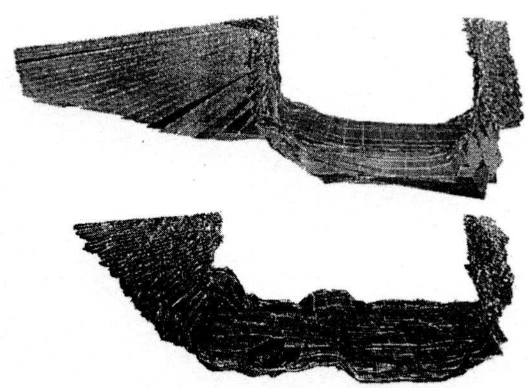

Fig. 4. Local terrain maps produced by the laser scanner. Top: a clear roadway, bottom: a roadway with obstacles.

6. CONCLUSION

In this paper we have discussed a number of critical issues in obstacle detection for autonomous mining and construction vehicles. The key points are as follows:

[3] Radar or laser energy reflected away from the receiver or completely absorbed.

- There are two distinct approaches to the obstacle detection problem. Obstacles can either be detected directly, or free-space mapping can be employed.
- Most obstacle detection systems developed for automotive applications are not suited to the mine or construction site environments.
- The most successful obstacle detection systems so far have used laser scanners to map the local terrain.
- It is important that researchers and users of obstacle detection systems understand and agree on what they mean by fail-safety.
- It is theoretically impossible to create a fail-safe obstacle detection system that directly detects obstacles only and not free-space.

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